THE ORIGIN OF THE TEKTITES

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In this paper I propose to show that the forms and distribution of the tektites may be explained in terms of a shower of bodies formed by the ablation of a natural satellite of the Earth.

Such a shower was observed on February 9, 1913, in the view of several authorities. The origin of the shower is most easily explained in terms of a body ejected from the surface of the Moon.

Tektites may be defined as small glassy bodies containing no crystals whatever, with at least 65 per cent SiO_2, with about half of the remainder consisting of Al_2O_3, and bearing no relation to the formations in which they occur. Tektites are found in certain large areas, called strewn fields. The largest strewn-field covers most of Southeast Asia (billitonites, indochinites, rizalites, and tektites from Kwang-chow-wan, Hainan, and Siam); another strewn-field, possibly related, covers most of Australia (australites); a third lies in Texas (bediasites); a fourth in Georgia (Georgia tektites); a fifth in the Ivory Coast (no special name); and a sixth in Bohemia and Moravia (moldavites).

In addition to these groups of tektites, there are several other groups of bodies, which are attached to the class of tektites by some but not all authorities. Among these are the americanites, which have small crystals within them and which contain a considerable amount of water; the Libyan Desert Glass, which is almost pure silica and radically different from any other tektite in composition; and the Darwin Glass, which differs from other tektites in its very vesicular structure. All of these classes are excluded from the present discussion in order to narrow the issues.

The outer surface of many tektites, especially those which come from the older formations, is marked by intricate grooves which give it the appearance of a worm-eaten piece of wood. These effects are considered by some to be due to the action of soil acids (Merrill, 1911), (Lacroix, 1932). Merrill believed he had reproduced these markings by etching obsidian pebbles with weak hydro-

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fluoric acid. On the other hand, Oswald (1942) considered them to be the result of motion through the atmosphere; he points out that the coarse sculpturing is not found on broken surfaces of moldavites. Lacroix (1932) found the same for indochinites.

True evidence of motion through an atmosphere is apparently found in the australites. The question has been most carefully discussed by Fenner (1938). Fenner showed that most forms of australites are derived from a button-shaped type which consists of a central lens, surrounded by a flange (see Figure 1). The form was explained by him as the result of the ablation of an originally spherical body, rotating rapidly. He considered that ablation reduced the sphere to a lens, and at the same time a portion of the glass from the front side of the body flowed around the edge and formed the flanges. The explanation is supported by the flow lines which are visible in thin sections of australites (see Figure 1). Although only a minority of tektites possess fully-developed flanges, Fenner believed, on the basis of very extensive examination of thousands of australites, that the majority of them had possessed flanges at one time. He also showed that on many of the tektites which lack a circular outline, flanges had formed and been broken off.

Underlying these effects of weathering and ablation, Fenner (1938) believed that he could trace a sequence of forms characteristic of a fluid body in rapid rotation. The forms depend on the speed of rotation. In order from the slowest to the most rapid rotation, they include spheres, ellipsoids, oval bodies, dumbbells, and teardrop shapes. These last presumably correspond to the tearing apart of a dumbbell shaped body. Occasionally, there are found canoe shaped bodies, presumed to be the result of the tearing away of two teardrop forms from a central nucleus. Among these shapes, the spheres and the ovals are the commonest and the more extreme forms the least common. Fenner pointed out that this sequence of shapes is closely comparable with the shapes assumed on a considerably smaller scale by bits of hot slag called smoke bombs or slag bombs, which are ejected from locomotive chimneys. The comparison illustrates the fact that the forms of the tektites are comparable in detail with the forms of rotating fluid masses. In the case of all strewn-fields except the Australian strewn-field, the bodies themselves as they are picked up appear to resemble the forms taken by rotating fluid masses.

As mentioned above, the interior structure of the tektites is marked by flow lines, which are visible in thin sections. These marks were examined by Hammond (1950) who found that the streakiness was associated with strains in the glass of the order of 80 Kg/cm^2, which indicated to him that the glass had cooled at the rate of about 50° centigrade per minute especially between about 700° centigrade and 600° centigrade. Many tektites, especially bediasites (Barnes, 1939) possess elongated inclusions of lechatelierite, i.e. practically pure silica. In addition, many tektites contain small bubbles, which according to Suess (1951) "represent a fairly good vacuum". He finds a pressure of less than 10^{-3} atmospheres. The inside of these bubbles is stated to have a mirror-like sheen.

Spencer (1933) states that microsections of australites and indochinites show small black spots which have a metallic luster by reflected light. He compares these with the tiny spheres of nickel iron in the silica glass from Wabar and with similar tiny spheres found in Darwin Glass, which are attracted by a magnet.

The chemical composition of the tektites is illustrated in Table I.

TABLE I

Chemical Composition of Tektites and Comparison Substances

	Molda-vite	Bedia-site	Indomala-yan body	Austra-lite	Ivory Coast	Igast	Building Sandstone	Shale
SiO_2	80.73	73.52	72.26	76.25	68.60	80.82	84.66	60.15
Al_2O_3	9.61	15.88	13.18	11.30	15.80	9.93	5.96	16.45
Fe_2O_3	-----	0.45	-----	0.35	0.18	2.45	1.39	4.04
FeO	1.93	4.64	5.32	3.88	6.46		0.84	2.90
MgO	1.59	1.[illegible]	2.15	1.48	2.88	1.58	0.52	2.32
CaO	2.13	0.06	2.42	2.60	1.40	0.75	1.05	1.41
Na_2O	0.37	1.30	1.43	1.23	2.35	0.76	0.76	1.01
K_2O	3.60	1.73	2.15	1.82	1.92	3.13	1.16	3.60
H_2O	0.02	0.08	0.20	0.34	----	----	1.74	4.71

As compared to terrestrial rocks, the tektites clearly belong to the acid group

along with granites and the sandstones. They are clearly different from the basalts or the shales, which have around 50 to 60 per cent SiO_2. The most striking feature is the absence of water. According to Friedman (1958), most tektites have between 20 and 100 parts per million of water. In this respect, they are strikingly different from all terrestrial rocks. For example, obsidians according to Friedman, have from 800 to 3,500 parts per million. In almost all tektites, the K_2O exceeds Na_2O. The iron is mostly in the reduced state (FeO). According to Loewinson-Lessing (1935), tektites differ from all terrestrial rocks in showing a high acidity coefficient and a high RO/R_2O ratio.

Heide (1938) states that the concentration of nickel in the tektites in the Indo-Malayan strewn-field is greatest in the central zone (Billiton, Borneo, Cambodia, and Cochin-China) as distinguished from the border zones (West Siam, North Indochina, Philippines and Australia).

The gas composition of the tektites has been studied Döring and Stützer (1928), by Suess (1951), and Friedman (1958). Friedman's results appear to be the most precise; they supersede those of Döring and Stützer and indicate that there is not more than 1 part per million by weight of gas in the tektites.

Studies of the age of the tektites have been made by Suess, Hayden, and Ingraham (1951) and by Kohman and Ehman (1958) and Anders (1959). Suess, et al found from studies of the decay of potassium to argon that the age of the philippinites and australites were less than 70 million years. These ages are since the tektite was last melted. Kohman and Ehman attempted to determine the length of time during which the tektites had been exposed to cosmic rays in space. By determining the amount of aluminum 26 and beryllium 10, they concluded that the australites must have come from outside of the Earth's atmosphere and must have spent at least 1 million years in space. Anders was not able to confirm these results, using non-destructive techniques which should have been more efficient; the effect probably does not exist.

As mentioned above, the distribution of the tektites is peculiar. It is entirely unlike the distribution of meteorites. The latter is nearly uniform over the globe; apparent maxima in the meteorite distribution in temperate latitudes or in industrialized areas reflect no more than the interest of the inhabitants. The known tektite strewn-fields on the other hand have a tendency

as Nininger (1952) points out, to lie between 40° north and 40° south of the equator. This feature is probably real, since the areas involved are less carefully searched than areas such as western Europe, or the northern part of the United States, where no tektites have been found.

Within the individual strewn-fields there are large variations in density. Fenner (1938) remarks that Dodwell found 250 pieces in a single square mile. Beyer (1942) remarks that in some areas in the Philippines the density of tektites rises to 100,000 per square mile. Fenner (1935) in discussing the australite distribution points out that it is cut off at a definite line in the northern portion of Australia. He (1938) is emphatic about the statement that the distribution of australites which is found is very similar to the actual distribution in which they were produced. He discounts the possibility that its major features have been changed by the natives or by such agencies as birds. On the other hand, it is important to notice that in the minor features there must have been some redistribution of the australites since Baker (1937) refers to the discovery of 38 tektites on an old road built in 1879 and 20 on the surface of borrow pits made in the construction of the new road. These finds cannot possibly be explained except as the result of some agency capable of moving considerable numbers of tektites, since the australites as a group certainly date from a period several hundred thousand years ago.

A most important discovery was made by Lacroix (1935) who found a dense deposit of tektites in French Indochina. A single square meter furnished about 9.7 kilograms of fragments; another area of 9 square meters furnished 20.6 kilograms. Lacroix remarks that the pattern of the flow marks in the glass was not as distorted as usual, suggesting slower cooling. He found a similar deposit in Cambodia. They appear to represent falls of single large blocks.

Beyer (1940) has drawn attention to the fact that in the Indo-Malayan fall there are 4 different size groups, which occur in different areas. He points out that the rizalites from the Philippines, which lie furthest east are the smallest and the tektites of Cambodia and French Indochina, which lie furthest west are the largest. This fact is undoubtedly of great significance for the question of the origin of the tektites. With reference to the time of origin, the same author states (1942) that the australites are post-Pleistocene. The

moldavites are from the Helvetian (mid-Miocene) and the Ivory Coast group are from the Mesozoic. Barnes (1939) states that the bediasites are Eocene.

In the light of the above facts, we shall attempt to trace the origin of the tektites. The first question to be asked is whether they are from a terrestrial or a non-terrestrial source.

It has been held ever since the first paper of F. E. Suess on the subject (1898) that they come from some extraterrestrial source. Suess gave two reasons for this in his early paper: First, the alleged flight-markings on the moldavites; and second, the fact that their composition wherever they are found, is always approximately the same and is totally unrelated to the composition of the local rocks. The argument from the distribution has been greatly strengthened since Suess' time by the extension of finds in the Indo-Malayan strewn-field, which covers a very large area with high chemical homogeneity. In addition, the finding of empty bubbles in some of the tektites by H. E. Suess points strongly to the formation of the tektites in an area of low atmospheric pressure. An alternative explanation for the bubbles in terms of steam which afterwards condensed and was absorbed in the rock is hard to reconcile with Friedman's discovery of the extreme dryness of tektites. If the tektites were permeable to water vapor it is very difficult to see how they could maintain for several millenia a water vapor pressure which is lower on the inside of the bubble than the water vapor pressure in the air outside.

The extreme dryness of the tektites differentiates them from all terrestrial rocks. It likewise differentiates them from the Libyan Desert Glass, which has apparently been formed in somewhat the same manner as the tektites but out of terrestrial materials. Friedman (1958) remarks that in order to dry out a terrestrial rock to this extent, it is necessary to heat it up to 2,000° centigrade.

Barnes (1939) put forward the hypothesis that the tektites are derived from sedimentary rocks. He based this on a comparison of their chemical composition with that of sandstones and shales from the paper of Clarke (1924). The tables which he employed are listed in Table I. It will be seen at once that the shales are not actually comparable with the tektites, since the average shale has less silica than any tektite. This difference is borne out by more recent studies such as those of Pettijohn (1957) which show that only the small group of siliceous

shales overlap the tektites in silica content. According to Mason (1958) 82 per cent of the sedimentary rocks are shales, 12 per cent are sandstones, and 6 per cent limestones. Thus, 7/8 of the sedimentary rocks can be excluded at once as sources of tektites.

In studying sandstones, Barnes used the building sandstones (Clarke, p. 463, col. G) rather than sandstones in general (Col. F). The effect of this choice is to reduce the lime content, since builders tend to avoid calcareous sandstones because they do not weather well (Clarke, p. 461). In justification of Barnes' choice, it may be urged that a tektite with a high lime content would crystallize thus becoming unrecognizable. Again the alumina of the sandstones quoted by Barnes is lower than that of any tektite unless we include Libyan Desert Glass.

Mason (1959) pointed out that igneous rocks could be found whose compositions matched the tektites much more closely than this; he tabulated for each group of tektites an igneous rock analysis which matched it surprisingly closely. Urey (1959) replied by listing sedimentary analyses from Pettijohn (1957). Nearly all of these were of sandstones, with the exception of a group of siliceous shales, thus confirming what has been said above to the effect that the tektites are chemically more like sandstones than like any argillaceous (clayey) rock. On the other hand, of the 22 analyses referred to by Urey (1959), 19 show an excess of soda over potash, and the other 3 a very slight deficiency; in the tektites on the other hand, the analyses nearly always show an excess of potash.

The extent of the difference between the tektites and the terrestrial rocks is illustrated by Fig. 2 prepared by J. Hochman and the writer. We employed the ratio of Mueller (1915)

$$m = \frac{FeO \quad MgO}{Na_2O \quad K_2O}$$

It was noticed, however, in agreement with Loewinson-Lessing (1935) that the success of this ratio in separating igneous rocks from tektites was a function of silica content. We, therefore, plotted this ratio against silica content and found a clear separation between the igneous rocks and the tektites. It is very clear that the tektites were not produced from igneous rocks. The distinction between the sedimentary rocks and the tektites is not as clear.

It is often stated that no tektite has ever been seen to fall. On the other hand, Brezina (1904) drew attention to the chemical resemblance between the

tektites and the object reported from Igast, Esthonia, by Grewingk and Schmidt (1864) as an observed fall. The composition of the Igast object is shown in Table I; it is seen to resemble closely that of a high-silica tektite such as a moldavite. The fall was unusually well-observed, there being two witnesses, one facing the point of fall and only 50 feet away at the instant of fall. The fall itself was unmistakable, having produced a flash and a detonation. The pieces were found under some linden trees which had been cut by the detonation; they were loose on the grass.

Despite the chemical similarity, the object is physically unlike a tektite; it resembles a slag containing unmelted grains of sand and feldspar. Some of the smaller pieces appear to have been partially melted and dripped (abgetropft) from larger masses. In the oxyhydrogen flame, the mass melts at about 2000° C; if there is an excess of hydrogen, the material becomes a streaky, olive-green glass, free of bubbles and transparent in places. Grewingk and Schmidt were engaged in a geological survey of this area at the time, and they assert that the object is not a fulgurite and that if it is of terrestrial origin, they do not know where to find the source-material.

On the other hand, Michel (1913) who has been followed by most other meteoriticists, classified Igast as a pseudo-tektite on the ground of the difference in structure. Michel considered that it might be the product of a glass-factory or a brick kiln.

For the present purposes, there are strong reasons to reject Michel's arguments, since:

a. Suess has pointed out (1916) that it has been established by numerous investigators that glasses of the composition of moldavites do not occur;

b. bricks normally contain more alumina and less silica than Igast.

In what follows, it will be assumed that Igast is a genuine fall of an object closely related to the tektites.

In summary, therefore, it is considered that the tektites are probably of extra-terrestrial origin for the following reasons:

a. Their chemical composition is unrelated to that of the formations in which they are found.

b. The composition is peculiar; all tektites have certain chemical chara-

cteristics which distinguish them from all igneous rocks and from nearly all sedimentary rocks (in addition to those listed in c. and d. below).

c. They are dryer than any terrestrial rock.

d. Their voids are reasonably good vacua.

e. Some of the (the australites) appear to have suffered ablation in flight through the atmosphere. The forms of the rest are those of rotating fluid masses; they are not inconsistent with flight through the atmosphere.

f. The Igast object appears to represent an observed fall of a body closely related to the tektites.

If we admit that the tektites are of extra-terrestrial origin than it is at once evident that they have not arrived in the same way as ordinary meteorites. The first distinction is in their distribution. As pointed out above, the tektites occur in large patches whereas the meteorites occur more or less uniformly over the whole surface of the Earth. Urey has pointed out (1955) that it is not possible to explain this difference on the ground that the tektites have passed through space in the form of dense clusters. He shows that a cluster of the type required to produce the observed distribution of australites by direct impact would be unstable and would be torn apart by the Sun's gravitational attraction in a relatively short time. He points out that a density in excess of 10^{-e} grams per cubic centimeter is needed for gravitational stability at the Earth's distance from the Sun. A possible answer to this argument was given earlier by Fenner (1938) and La Paz (1938) who drew attention to the great meteor procession of the 9th of February, 1913. The important point is that it is an observed case of a cluster of meteors some 1500 miles long and 3 or 4 miles in breadth. Fenner mentioned also that the meteoric procession was somewhat narrow compared to the observed breadth of the tektite distribution. Possible methods of meeting this objection will be discussed below.

The second significant difference between the tektites and the meteorites is indicated by the fact that although the meteorites have a crust which is a few millimeters thick or less, the tektites give evidence of deeper melting. The case is clearest for the australites, where the glassy material appears to have melted and then flowed back over the surface to form the flange. In discussing this problem, Fenner draws attention to some calculations of Öpik (1937). The

essence of the difficulty is that the heating from the atmosphere is so great and the loss by evaporation so rapid that in an ordinary meteoric stone the liquid layer is extremely thin. For this reason it is ordinarily impossible for orderly flow to take place. We conclude from this that the australites, if extra-terrestrial, should have arrived at the Earth along paths which would produce lower temperatures for a longer time than the paths of ordinary meteorites. This fact points in the same way as the evidence from distribution; namely, to the assumption that the meteorites arrived along a path similar to that of the great meteor procession of the 9th of February, 1913. The meteor procession followed a path which was very nearly parallel to the surface of the Earth and extended for some 5 or 6 thousand miles. The velocities of the bodies of this shower were extraordinarily low, certainly less than 10 kilometers per second. They thus provided the necessary conditions of time and temperature for liquid flow.

An interesting and suggestive idea was proposed by Hardcastle (1926) and Hanuš (1928). They supposed that the tektites were formed during the passage of a stony meteorite through the air. They felt that the surface of the stony meteorite would be liquefied and that drops would form, which on being sprayed off into the air would give rise to the characteristic forms of the tektites, as they cooled. This theory in its original form encounters the difficulty that the chemical composition of the tektites is entirely different from that of the stony meteorites and that there are cases in which a liquid crust has formed on a stony meteorite which has been recovered and found to have the same composition as a stone (Farrington, 1877). On the other hand, if we suppose that the matrix from which the tektite was removed by ablation was of the same chemical composition as the tektites, then the Hardcastle-Hanuš mechanism gives a logical explanation of the formation of the tektites. Hanuš's theory was further developed by Oswald (1942). It will be seen that this theory requires that the tektites should have been completely melted while in the atmosphere. Since some of them are several centimeters thick, it reinforces the above mentioned requirement for a long and slow heating in the formation of the tektites. This mechanism, on the other hand, explains the low argon ages of the tektites as due to the escape of argon during the reentry into the atmosphere.

Krinov (1959) found that small iron droplets were formed on the surfaces

of the Sikhote-Alin meteorite and some others, and swept off by the air blast during the fall of the body. The droplets are chiefly spherical, with occasional spheroids, teardrops, and bottle-shapes; but they are much smaller than tektites, ranging from 0.01 to 0.7 millimeters. They closely parallel the conditions suggested by Hardcastle, except that the greater heating and the more violent airblast have combined to produce a thinner liquid layer and smaller droplets.

If we suppose the parent body to have had a composition similar to that of Igast, then the smaller bodies which have dripped off might be considered as representing the first stages in the formation of a normal tektite. In later stages, the mass would be melted; but individual grains of sand might still be detectible as the long filaments of lechatelierite which Barnes found in the bediasites. It should be mentioned that Fenner (1938b) supported Hardcastle's idea.

Summing up, therefore, the distribution of the tektites suggests that they have reached the Earth along paths similar to that of the great meteor procession. The depth to which melting has proceeded suggests the same origin. We shall, therefore, proceed to a detailed study of what is known of the Meteor Procession of February 9, 1913.

The accounts of the meteor procession were collected by Chant (1913a, c,). The procession was first seen in the towns of Mortlach and Pense in Saskatchewan. It was then observed at many points in the province of Ontario. It left Canada passing near Toronto where loud detonations were heard. In the United States, Chant collected only two accounts; but the section of the path from Buffalo to New York was filled in by accounts uncovered by Mebane (1956). Between New York and Bermuda it was sighted by 3 ships whose accounts are given by Pickering (1923b). It was then sighted at Bermuda, (Chant, 1913b). Beyond Bermuda, it was observed by 2 more ships whose accounts were uncovered by Denning (1914, 1915).

The procession, as observed, consisted of 5 or 6 groups of meteors each of which consisted of half a dozen individual bodies. All of the objects followed the same path across the sky; the total duration of the display was a matter of about 5 minutes. Each individual group took something like a minute or two to cross the sky. The individual meteors had tails attached. As they passed across the sky, they frequently broke up. The individual bodies released small sparks which were observed to go out. The angular width in the sky occupied by

the whole procession was not more than about 4 or 5 degrees; by triangulation, Pickering estimated the physical size to be on the order of 4 or 5 miles. According to Mebane there is at least one observation by the Weather Bureau at Alpena, Michigan indicating that the later members of the shower followed a path which was west of that of the earlier members.

The Canadian and British computers who studied the shower at the time felt that the bodies of the shower must have been traveling in a satellitic orbit around the Earth. (Chant, 1913a; Davidson, 1913a,b; Burns, 1913). This view was strongly espoused by Pickering (1922; 1923a,b,c) in a series of articles in Popular Astronomy. In these calculations it appeared that it was not possible to obtain an accurate idea of the time of flight of the object since the observers had not consulted their watches and since the procession itself took such a long time to pass a given point that it was difficult to define a reference time. The evidence for a satellite orbit lay in the fact that the bodies had been observed over an arc some 6,000 miles long at the height at which meteoric bodies can be observed; namely, between 40 and 60 miles. If it were certain that it was the same bodies that were observed throughout the whole track, there could be no question that their orbit was satellitic. However, Fisher (1928) remarked that the detonations heard near Toronto meant that some of the pieces must have been below 24 miles, and that these bodies could not have gone much further. He felt that this "satellite meteor" as he called it, must have consisted of a group of bodies of which only the lower members were incandescent at any one time. He suggested that the bodies had been arrested by passing through the denser atmosphere at the Earth's equatorial bulge. He recalculated the orbit which Chant had originally given, allowing for the effect of the Earth's rotation. In 1939 Wylie (1939) attacked the whole concept of a satellite meteor. He gave a radiant which, he stated, would satisfy the observations within the errors of untrained observers. He also asserted that the detonations heard in Toronto must have belonged to a body which was only accidentally associated with the meteor shower. The investigations of Mebane, however, showed that the noises had progressed in New York State as far as Elmira. This appears to demonstrate that the connection between the detonations and the meteor shower is real. O'Keefe (1959) calculated the apparent radiants at each of the observations stations which would have resulted from Wylie's true radiant; it appeared that Wylie's radiant could not account

for the observations of the two southern most ships at all; the shower should have been invisible from these points. It also appeared that no possible rearrangement of the space radiant, which would make the shower visible at the two southern most stations would agree with the firm statements of numerous witnesses in Canada that the flight was nearly level. It appeared that no explanation of the shower was possible except that it was satellitic.

A remarkable feature of this shower is its resemblance to the descent of Sputnik II (1957 Beta I) as described by Jacchia (1958). Both objects were visible by their own light (as distinct from reflected sunlight) over a path some thousands of miles in length. Both developed long tails. In the case of Sputnik II, the tail was some 100° long just before the body disappeared; the tails on the Meteoric Procession were only about 10° - 15° in length. The tail on Sputnik II was not attached to the head, but separated from it by a dark space. According to Mr. W. L. Haight, of Parry Sount (Chant, 1913), the same was true of the largest body of the 1913 shower; Mr. Haight made a drawing which Chant reproduced to illustrate this point.

Small "globules" were observed to detach themselves from time to time from the rocket, develop tails, and disappear. Many witnesses described the same phenomenon with respect to the Meteor Procession; e.g., Col. A. R. Winter, Hamilton, Bermuda, speaks of the body "coruscating, or breaking into small pieces. As these pieces separated from the parent body, they developed trails of sparks and gas". Jacchia noted that the particles which separated from the rocket were probably liquid, since they tended to break in two. This phenomenon was not specifically noted in the Meteoric Procession; but the descriptions do not by any mean exclude it. If the objects shed in this way were liquid drops, they would correspond almost exactly to the requirements of Hardcastle's theory.

The globules detached from 1957 Beta had masses in the range of the tektites. This follows from the total amount of radiation produced. With mass M and velocity w, the available energy, which is for all intents and purposes only the kinetic energy of the rocket, is $1/2\ M\ w^2$; the integrated light, assuming constancy is jt, if j is the average intensity and t the duration. Hence (Öpik, 1958) we write

$$jt = 1/2\ \beta M\ w^2$$

where β is the so-called luminous efficiency. The luminous efficiency would be

1 if the eye were as sensitive at all wavelengths as it is at the peak of visual efficiency around 5100 Å.

Converting to logarithms and replacing intensity by "absolute magnitude" m, equal to the apparent magnitude which the object would have at a distance of 100 kilometers, Öpik finds (p. 148)

$$\log M = 10.02 + \log L - \log \beta - 3 \log w - 0.4m$$

Here the time has been replaced by the quotient of path-length L and velocity.

To evaluate β, we make use of the observations on the integrated light of the rocket. According to Jacchia, the absolute magnitude of the whole object including the coma and tail was -9 to -10 at maximum brightness near latitude 13°. It is clear that the total brightness is what should be taken rather than the luminosity of the head alone, since the source of the energy in the tail was the energy of the globules and gas liberated from the head. It appears that the head lost most of its kinetic energy through mass-loss, since the tail, which was fed by debris from the head, was, together with the coma, several magnitudes brighter than the head alone.

It should also be mentioned that by this method we obtain the total mass even if the whole mass is not consumed, since the whole of the kinetic energy is certainly consumed in the atmosphere. When any meteoric body weighing less than hundreds of tons reaches the ground, its velocity is so low that nearly all the kinetic energy has been wrung out of it.

The path length which should be adopted is that along which the body was at or near maximum brightness. Over the continental United States, the absolute magnitude was near 0, i.e. about a ten-thousandth of the maximum brightness, hence this portion of the path may be ignored. There follows a gap in which no observations were made. Then, from about latitude 24° to latitude 10°, a period of 247 seconds, the satellite was reported as highly luminous. During this time, it appears from Jacchia's orbit that the satellite covered a distance L of 1690 kilometers at an average speed w of 6.8 kilometers per second. These last values are adopted.

The mass of 1957 β has been estimated by NASA as 4 tons, (NASA, 1959). Substituting these values in Öpik's formula, we obtain

$$\log \beta = -2.05.$$

This value is remarkably large. Possible sources of error are:

a. The estimated path-length. Judging from the light-curve given by Öpik, the path-length which should be used with the maximum luminosity to give the correct integrated brightness is roughly twice the distance from the point of maximum brightness to the end. In our case, this would work out to roughly 900 kilometers rather than 1700.

b. The estimates of the maximum total brightness. These were particularly difficult because it was necessary to obtain from inexperienced observers an estimate of the integrated stellar magnitude of a diffuse object 20° to 100° in length. On the other hand, the assertion that an illumination was noticed on the ground sets a definite lower limit to the total radiation which is not far from the brightness given by Jacchia. Moonlight is not conspicuous before first quarter, which corresponds to about magnitude -9 to -10.

c. The estimates of the mass of the satellite. At the time of the launching of the Atlas satellite the Soviet embassy protested against statements that the weight of Atlas was as great even as the weight of 1957α_1, the rocket carrier of the first Russian satellites. Since Atlas weighed 4 tons, there is an implication that the weight of 1957 Beta was substantially greater.

From all of these sources of error, we can reasonably expect to explain a discrepancy of 10 in the value of the luminous efficiency. On the other hand, the calculation of the luminous efficiency by the methods given by Öpik (1958) chapter 8, yields an efficiency of the order of 10^{-4}. The discrepancy seems to be more than observational error.

The luminous efficiency is divided by Öpik into three components, namely the component due to collisions of atoms vaporized from the meteor with air molecules, that due to collisions among the vapor atoms, and black-body radiation from the solids and liquids present. Of these, the first in our case has an efficiency of 4×10^{-5}; the second of zero, and the third of from 10^{-4} to 10^{-5} in the range of temperature from 1800° to 2400°, i.e. roughly from fusion to vaporization.

There does not seem to be any process which would enhance the luminous efficiency due to the first two processes; but there may be an overlooked factor in the third process. If the gaseous iron from the rocket is present in sufficient quantity, it is imaginable that a part of it would recondense into liquid

smoke droplets after the vapor had left the surface of the rocket and cooled slightly. This would leave a gap between the head and the tail. The smoke particles would still possess most of the velocity of the rocket; owing to their larger areas they would have considerably higher radiative efficiency. In this way, most of the energy might escape from the mass in the form of radiation.

In favor of this hypothesis is the fact that one of the observers reported a black smoke trail left behind by the object. In addition it is noteworthy that most of the luminosity came, not from the head, but from the tail. It does not appear that the globules of the tail can explain the extra brightness; one observer states that there were about thirty in view at once. Since each had a brightness of about -3, the total luminosity should have been about -6; but what we have to explain is a luminosity of -9 to -10. We cannot suppose that the luminosity was due to many small droplets sprayed from the object because there is a lower limit to the size of droplets which can be sprayed, and this limit is near the size of the globules observed.

On this hypothesis, the dark region between the head and the tail is like the transparent section of the steam column just beyond the spout of a teakettle, or the opening of a locomotive smokestack where the steam is present but in gaseous form. The total luminous efficiency should be close to the black-body luminous efficiency for some temperature lower than the temperature of rapid vaporization. If the temperature is as high as 2000°, an efficiency of 4×10^{-3} is to be expected.

Since the calculation of the masses of the globules is exposed to much the same sources of error as that for the satellite as a whole; and since the mechanism of light production is likely to be the same, we shall employ the same luminous efficiency. This assumption permits us to consider the ratio of the mass of the globule to that of the satellite as a whole as equal to the ratios of the product jt.

The observers on the ship Regent Hawk reported, according to Jacchia (1958) that the globules were about twice as bright as Sirius, i.e. about magnitude -2.4, apparent, or, allowing for the distance, -4 "absolute". The same observers stated that the globules lived for about 1 second. The ratio of luminosities, globule to satellite is therefore 160; the ratio of times is 250; the ratio of

masses comes out as 40,000. The masses of the globules are thus about 100 grams. The corresponding radii are about 1.5 centimeters if they are assumed to be aluminum.

Jacchia points out that the bodies were probably liquid, since they were observed to break in two by observers in Barbados. He calculated the height of the object near Barbados as 70 kilometers; at this height, with the velocity of 6.8 kilometers per second, and air density $\rho = 10^{-7}$ g/cc, according to the Rocket Panel, (Öpik, p. 13), the drag pressure is given by Öpik, (1958, p. 37, equ'n 4-23).

$$p_s = 1/4 \rho w^2$$

$$p_s = 11{,}000 \text{ dynes/cm}^2, \text{ or } 0.167 \text{ lb./in}^2.$$

This pressure is less than 1 thousandth of that necessary to break even the weakest ordinary kinds of stones or bricks.

It is, however, sufficient to break up a liquid iron globule of this size. The critical radius r_Λ is given by Öpik (1958) p. 84 as

$$r = \frac{4s}{p_s}$$

With a surface tension s_Λ of 1200 dynes/cm. as for iron, r is 0.4 centimeters; for aluminum the surface tension is 840 dynes/cm yielding a radius of 0.3 centimeters. (from total light and from surface tension)

The discrepancy between the two determinations of the radius r_Λ is probably not significant; for example it could be reconciled by a change of 4 kilometers in the assumed height. The important point is that the globules were in the size range of the tektites, not in the size range of the small iron droplets (less than 0.04 cm. in radius) which Krinov (1959) has found coming from ordinary iron meteorites. If we attribute to the rocket drops masses of the order of those found by Krinov, we have a discrepancy in the luminous efficiency which is five orders of magnitude worse than that found above for the rocket as a whole. The masses were unquestionably in the fractional kilogram range, not the milligram range.

A critical test of the drop explanation of the sparks seen in 1957 Beta can be made by calculating the temperature at the top of the liquid layer on the meteor from which the flow takes place. This test is critical because if the

temperature is too high, vaporization will take the place of liquid flow. It is ordinarily found that iron will flow under meteoric conditions, but stone will not.

The ratio of heat lost by radiation to that lost by evaporation is given by Öpik (1958) Table XXXII, p. 98; it appears that the critical surface temperature for iron is 2100°; below this temperature liquid flow is expected to occur freely because evaporation is less important than radiation as a method of heat loss. Hence, the liquid layer will not be greatly thinned by evaporation.

To calculate the actual surface temperature, we start at the bottom of the liquid layer, where the liquid is in contact with the solid and the temperature is that of fusion, about 1800°. The difference, ΔT between this temperature and that at the top depends upon the rate at which heat is being supplied, the thickness of the layer, Δr and the thermal conductivity k_t (Öpik, p. 104, eq'n 6-43)

$$\Delta T = \frac{1}{2} \frac{\gamma \rho w^3 \cos\alpha \, \Delta r}{k_t}$$

where γ is the fraction of the incident kinetic energy which goes to heating the surface, and α is the angle between the normal to the surface element and the direction of motion of the body. For the present calculation, we set α equal to zero, since this will be the critical value.

The calculation of γ is carried out according to Öpik's precepts for a large meteorite; it is found to be 0.0545 for iron. To calculate Δr, we have to consider the equilibrium between the rate at which fluid is produced by melting, and the rate at which it is removed by drag. The most important parameter here is the viscosity, η, which, for iron has the value 0.01 poises. From the above considerations, Öpik (p. 103, eq'n 6-38) finds the equation

$$\Delta r = \left[\frac{r w \eta \gamma}{2 h_f \delta (1-q) \cos\alpha} \right]^{1/2}$$

where δ is the density (7.8 for iron) and q is related to the coefficient of accomodation χ = 0.522 (Öpik, p. 51, Table X) by the equation

$$q = \sqrt{1 - \chi}$$

Because of the low viscosity of liquid iron, we find that the liquid layer

is very thin--about 1.7×10^{-3} centimeters. The corresponding value of ΔT is 0.3°; and the temperature at the surface is therefore practically at the temperature of fusion, 1800°. At this temperature, about 12 times as much heat is lost by radiation as by evaporation; and we can conclude that the iron will actually flow in the manner required by this hypothesis.

We conclude, therefore, that as 1957 Beta descended through the atmosphere, it sprayed drops of liquid iron whose size was comparable to that of the tektites.

The similarity between the phenomena of the descent of 1957 Beta and those of the Meteor Procession suggest that very similar processes were at work. There are, however, some important differences in the physical parameters, especially the viscosity and the surface tension. On the observational side, the heights are not as well determined, principally because we do not have the assurance that the bodies seen at one point are the same as those seen at another, and hence the dynamical arguments cannot be employed with confidence. Nevertheless, it appears that the same physical assumptions used to explain 1957 Beta will also explain the phenomena of the Meteoric Procession.

To determine the mass of the largest body, we note that out of over a hundred reports, only at Fonthill, near Niagara Falls, and at Ft. Francis, Ontario, did observers report (Chant, 1913) a noticeable illumination of the ground. Both were close below the path. Hence the magnitude was between -4, at which the effect is barely detectible when searched for, and -10, at which is is conspicuous (e.g. the Moon at first quarter). A magnitude of -7 as seen from the ground appears reasonable. The observers quoted were at ground distances of 10 and 55 kilometers respectively from the trace of the path on the ground; allowing for a height of 70 kilometers, the distance corrections are 0.25 and 0.75 magnitudes; the "absolute magnitude" thus appears to have been about -6.5.

The minimum value which can be taken for the path-length is the distance from Ft. Francis to Fonthill, roughly 1250 kilometers; the adopted value is 2500 kilometers, namely the distance from Mortlach, near Regina, Saskatchewan, where the meteors were first noticed, to the area of Toronto and upstate New York, where loud detonations indicated that at least some of the larger bodies fell. The velocity is taken as 6.8 kilometers per second, as for the terminal phase of 1957 Beta; the observations of time are not sufficiently accurate to permit a correction of

this calculation. If, however, the 1913 shower consisted of bodies in orbit around the Earth, as maintained by most students, the velocity cannot have differed greatly from this value.

For the luminous efficiency, a value of 10^{-2} is taken. This value probably includes some effects of systematic error in the estimates of brightness, as for 1957 Beta. The mechanism of light production may have been similar, since several observers reported smoke, and since a dark space was seen behind the head of the largest body. If, however, the radiation was actually from a vapor, the efficiency should be lower for tektites than for iron by a factor of 10.

We find, for the mass of the largest body, from equation 8-26, (Öpik, 1958) the value 370 kilograms.

The smaller bodies were seen to cross the entire field of view, in general, although some were seen to break up. We may, therefore, assign to them lives of the order of 1 minute, and path lengths of the order of 500 kilometers. Their brightnesses were estimated by observers at Aylmer and Ridgeway; in addition, there is the drawing of Mr. Gustave Hahn. From all of these, the "absolute magnitude" comes out, with reasonable consistency, as +1.8. The resulting masses are about 35 gms.

The "sparks" which were observed are poorly described; their luminosities must have been considerably less than those of the lesser meteors, and brighter than the lower limit of meteor magnitudes, which is about the fifth magnitude; it is reasonable to adopt an absolute magnitude of 4. Their durations may have been only a second or two, from the word spark, used with respect to them. Adopting 10 km. as the path length, the masses are found to be about .1 gm.

The determination of the height presented considerable difficulty because of the presence of large systematic and accidental errors in the observations. (Chant, 1913a, Denning, 1913, Denning, 1915, Denning, 1916, Davidson, 1913a, Chant, 1913c). The most straightforward procedure is to apply a reduction of 1/3 to all reported angular altitudes, as recommended by Denning (1913). The result is given by Chant (1913c) p. 444 as 70.1 kilometers. (See also Denning, 1915, 1916, where a value of 42 miles or 67.5 km is his last result for the height).

From Öpik's formulas we calculate, as above, a radius of 0.14 cm. for the sparks. This is to be compared with a radius of 0.21 cm. which follows from the

calculated mass and an assumed density of 2.5. The agreement is satisfactory.

The most critical point, however, is whether the liquid stone will flow at all. As mentioned above, Fenner (1938) quotes an unpublished remark of Dodwell based on Öpik's work (1937) to indicate the difficulty of accounting for flow in stone meteorites. The point is that the heating due to friction is so strong that in an ordinary meteorite, the liquid layer is evaporated as fast as it is formed. The depth is thus very small; and because of the high viscosity of liquid stone, flow does not take place. In the present case, however, flow will occur, since the heating of a body in a satellite orbit is much less than that in a normal meteoric orbit.

To prove that flow can occur for a body in a satellite orbit, we first note that the treatment of a stone object cannot be the same as that for the iron object. When we perform the same calculation as that made for iron, we find that the losses by vaporization exceed those by radiation. Hence the temperature at the top of the liquid layer will be controlled by the equilibrium between vaporization and heating, rather than that between flow and heating as in the case of the iron.

We proceed to make a numerical calculation for the case represented by the smaller bodies of the 1913 shower; 35 gram spheres, of density 2.5 and radius 1.5 cm. traveling at 6.8 km/sec at a height of 70 km.

The heat received per second is given by

$$\tfrac{1}{2}\gamma\pi r^2\rho w^3\sin^2\alpha$$

where γ is the coefficient of net heat transfer to the meteor, r the radius of the body, ρ the atmospheric density, w the velocity, and α the angle from the direction of motion to the radius through the spot under consideration (Öpik, 1938, p. 37, eq'n 4-25; p. 102, eq'n 6-37). The average heat supplied from $\alpha = 0$ to $\alpha = \alpha_0$ per unit area is found to be

$$U = \frac{1}{4}\gamma\rho w^3\frac{\sin^2\alpha_0}{1-\cos\alpha_0}$$

The half-energy range λ is about 0.6 cm. for the pressure of 9.74×10^{-8} gm/cc (which corresponds to 70 kilometers of height, according to the Rocket Panel). The quantity γ is determined from λ and α, the coefficient of accomodation for

which a value of 0.722 follows from Öpik (1958, p. 51). The resulting value of U, for α_0 equal to 45^0 is 7.78×10^9 erg/cm.sec. This heat is expended on the following:

a. raising the stone to 2100^0; this requires roughly 2.1×10^{10} erg/gm;

b. melting the stone: 0.3×10^{10} erg/gm

c. vaporizing the stone, 6.0×10^{10} erg/gm. Total, 8.4×10^{10} erg/gm.

Hence, the amount of stone vaporized is 9.2×10^{-2} gm/cm^2.sec. The corresponding temperature, calculated from the formula of Öpik, p. 161 is

$$T = 2094^0$$

The difference between the top and bottom of the liquid layer is then $\Delta T = 294^0$, assuming a temperature of fusion of 1800^0.

Assuming transport of heat by conduction we have

$$\Delta T = \frac{U \Delta r}{k_t}$$

hence, employing a value of the thermal conductivity k_t of 2×10^5 erg/cm.sec.deg (Öpik, p. 162)

$$\Delta r = 7.6 \times 10^{-3} \text{ cm.}$$

We next calculate the tangential component of the drag $p_t = (1 - q)\rho W^2 \cos\alpha \sin\alpha$; we find 1.07×10^4 dynes/cm^2 at an angle $\alpha_0 = 45^0$ from the direction of flight, from Öpik, p. 102, eq'n 6-36, using the definition $q = \sqrt{1-\chi}$ (Öpik, p. 35). This drag will produce an average velocity of flow v, given by the equation (Öpik, p. 103)

$$\frac{2v\eta}{\Delta r} = p_t$$

whence v = 0.81 cm/sec., assuming the value 50 for the coefficient of viscosity of liquid stone.

A layer thickness Δr of 0.1 millimeters and a velocity v of 1 cm/sec. account in a satisfactory manner for the sparks of the 1913 shower. They also account for the appearance of the australites. Here we see that the flange has been produced by the backward flow of a thin liquid layer. The observed flange thickness would have been produced by this process in a matter of a few tens of seconds, which is the time available. Most of the matter is lost by evaporation.

It appears, therefore, from a preliminary physical analysis, that the Hardcastle-Hanuš mechanism for the formation of the tektites will work in a satisfactory way, provided that the tektites entered the atmosphere along trajectories which are nearly parallel with the horizon. The importance of this condition was pointed out by Öpik in private conversation; he remarked that this equation 5-35, p. 76 shows the dependence of the effective density in the atmosphere (the density at the level at which the ablation effectively takes place) on the cosine of the zenith angle. Meteorites coming in at steep angles suffer ablation at low levels in the atmosphere; those coming in at shallow angles are ablated at much higher levels and low densities; they should therefore yield much larger droplets. The equation is

$$\rho = \frac{\phi r_0 \cos Z}{w^2} ;$$

here ϕ varies rather slowly with the height.

The great meteor procession thus has the principal characteristics required to explain the observations of tektites. Because of the form of its orbit, falls must have taken place from it over a wide area, although none has been recovered. The area was extended in length by the long distance over which the shower passed it at small elevation; it was extended in longitude by the rotation of the Earth underneath the shower during the time that the shower was passing overhead. This is the probable explanation for the observations made by the Weather Bureau at Alpena referred to above. It is true that in this case, the area covered must have been narrower than either the australite strewn-field or the Indomalayan strewn-field. On the other hand, it would seem reasonable to suppose that in some cases bodies

of ~~the~~ a cluster have survived several passages through the lower atmosphere, and hence that the strewn-field consists of several narrow zones at a distance from one another. If the shower had covered a larger portion of the orbit, this would likewise have tended to broaden the strewn-field in longitude. The latitude of the strewn-field was presumably that of the perigee of the orbit. The extent in latitude presumably depended on the distance over the Earth at which the bodies were near perigee; i.e., the eccentricity of the orbit. It is also natural to relate the observed concentration of tektite falls toward the equator with the fact that the Earth's atmosphere is about 15 times denser for a given value of the radius vector at the equator than at the poles (O'Keefe, 1958).

Let us now turn to the previous history of the great meteor procession. It is hard to doubt that this was originally a single body which was broken up by drag in the Earth's atmosphere. Had it not been a single body then, as pointed out by Urey (1955), its lifetime as a cluster whether in the solar system or in the neighborhood of the Earth would have been very short. Since the density of the cluster as observed was well below Roches' limit, tidal forces have disrupted it very rapidly.

It is possible to guess approximately how long a time passed between the breakup of the original body and its first sighting. The maximum range in the heights of visible fireballs is about 55 miles. This would correspond to a range in the period of about 1.6 minutes. Hence the observed range in time of passage, which amounted to not less than 2 minutes, required at least one, and probably two or more orbital periods to establish. In other words, the breakup of the original body probably occurred more than 1 1/2 hours before its first discovery and less than 12 hours.

As we look at the previous history of this body, it is plausible to assume

that it resembled the history of the artificial satellites which ended their lives with orbits which were so similar. That is to say, it is logical to think that the orbit had previously been both larger and more eccentric. As we go back in time, it is logical to think that we tend toward an extremely large and an extremely eccentric orbit.

The entry of the satellite into this orbit presents very great difficulties if it is supposed that it was captured in some way in space. The difficulty is the following: If the body had the velocity in space which corresponded to a normal meteoric velocity, then it might conceivably be captured into an orbit around the Earth by a single encounter with the Earth's upper atmosphere, losing at the same time enough energy to reduce its geocentric velocity from some 20 kilometers a second to something below 11 kilometers a second. But in such a body the next pass would have resulted in the fall of the body to the Earth, since it would have passed closer at the second perigee in all probability. In this case, we would not have had the observed nearly circular orbit, nor the observed spread of the bodies along the path. Encounters with the Moon can change the velocity by a maximum of 2 km/sec. It appears that the most plausible source for a body in a long lived elliptical orbit around the Earth is the Moon. Nininger (1943) suggested that the tektites originated as the result of the impact of ordinary meteorites on the Moon.

The theory of a lunar origin receives support from several other facts:

a. There is direct evidence from the length of the lunar rays that some material has been ejected from the craters with a velocity of the order of the circular velocity around the Moon. It is plausible to suppose that a smaller quantity reached the velocity of escape (Urey).
(Barabaschoff 1923, 1924, Markov, 1924, Wirtz, 1915, Schoenberg, 1929)

b. The reflecting properties of the lunar rays are best explained by transparent glassy spheres (O'Keefe, 1958). These suggest an acid silicate as the

principal constituent of the lunar crust. They are probably not identical with the tektites, but may have been formed by analogous processes in the fireball around the point of explosion.

c. The polarization of light from the Moon's surface suggests a finely divided acid silicate (Wright, 1928).

d. The radar reflectivity of the Moon is so low that it is hard to explain except as a finely divided acid silicate (Senior and Siegel, 1958).

It is therefore concluded that the Moon's surface has a chemical constitution similar to that of the tektites; and that its physical structure may be represented by the Igast object.

Certain conclusions about the nature of the processes which have formed the Moon follow from these ideas.

a. The lunar rocks appear to contain small but measureable quantities of chlorides; at least such are found in Igast.

b. The large ratio of uranium and thorium to radiogenic lead found by Tilton (1958) requires us to suppose that they were injected into the rock in comparatively recent times (not later than 50 million B. C.).

c. A considerable portion of the Moon's surface appears to consist of porous material. This is suggested by the Igast object, and supported by the extremely low value of the dielectric constant of the Moon's surface found by Senior and Siegel (1958). The value is so low that it can only be explained by a porous material.

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Bibliography

Anders, E., (1959), preprint (unpublished).

Baker, George, (1937), Proc. Roy. Soc. Victoria, 49, (n.s.) pt. II, p. 165.

Barabascheff, N., (1923), Ast. Nach, 217, 445.

Barabascheff, N., (1924), Ast. Nach, 221, 289.

Barnes, Virgil E., (1939), University of Texas Publication 3945, 477-656.

Beyer, H. Otley, (1940), Pop. Astr., 48, 23.

Beyer, H. Otley, (1942), Ann. Report Smithsonian Inst., p. 253.

Brezina, Aristi de, (1904), Wien, K. Akad, Wiss. Anzeiger, 41, 41.

Burns, Gavin J., (1913), Jour, of the British Astronomical Association, 24, 111.

Chant, C. A., (1913a), Jour. Roy. Ast. Soc. Canada, 7, 145.

Chant, C. A., (1913b), Jour. Roy. Ast. Soc. Canada, 7, 439.

Chant, C. A., (1913c), Jour. Roy. Ast. Soc. Canada, 7, 441.

Clarke, F. W., (1924), U. S. Geol. Survey Bulletin No. 770.

Davidson, Rev. M., (1913a), Jour. of British Astronomical Association, 24, 148, p. 149.

Davidson, Rev. M., (1913b), Jour. Roy. Ast. Soc. Canada, 7, 441.

Denning, W. F., (1913), Jour. Roy. Ast. Soc. Canada, 7, 404.

Denning, W. F., (1915), Jour. Roy. Ast. Soc. Canada, 9, 287.

Denning, W. F., (1916), Jour. Roy. Ast. Soc. Canada, 10, 294.

Döring, T. and O. Stutzer, (1928), Centralblatt für Mineralogie, Geologie und Paläontologie, Jahrgang 1928, Abt. A, p. 35.

Farrington, O. C., (1877), Mem. Nat. Acad. Sci., 13.

Fenner, Charles, (1933), Nature, 132, 571.

Fenner, Charles, (1935), Trans. Roy. Soc. S. Australia, 59, 134.

Fenner, Charles, (1938a), Proc. Roy. Soc. S. Australia, 62, 208.

Fenner, Charles, (1938b), Zentralblatt für Mineralogie, Geologie und Paläontologie, Jahrgang (1938), p. 220.

Fisher, W. J. (1928), Pop. Astr., 36, 398.

Friedman, I., (1958), Geochimica et Cosmochimica Acta, 14, 316.

Grewingk, C. and C. Schmidt, (1864), Archiv für die Naturkunde, Liv-Ehst-und Kurlands, 4 series, Mineralogical Sciences, 3, 421.

Hammond, Charles, R., (1950), Pop. Astr., 58, 345.

Hanuš, F., (1928), Rozpravy II Třídy Čes Akademie Roč XXXVII čís 24.

Hardcastle, H., (1926), New Zealand Journal of Science and Technology, 8, 65.

Heide, F., (1938), Zentralblatt für Mineralogie, Geologie und Palaeontologie, Jahrgang 1938, p. 359.

Jacchia, L. G., (1958), Smithsonian Astrophysical Observatory Report No. 15.

Kohman, T. H., Ehman, W. D., and E. Anders, (1958), Geochimica et Cosmochimica Acta, 14, 340.

Kuiper, G. P., (1954), Proc. Nat. Acad. Sci., 40, 1096.

Krinov, E. L., (1959), Sky and Telescope, 18, 617.

Lacroix, A., (1932), Archives du Museum National d'historie naturelle, Paris, Series 6, 8, 139.

Lacroix, A., (1935), Comptes-Rendus de l' Academie des Sciences de Paris, 200, 2129.

La Paz, Lincoln, (1938), Pop. Astr., 46, 227.

Loewinson-Lessing, F., (1935), Comptes Rendus, Acad. Sci. U. S. S. R., New Series, 3, p. 181.

Mason, Brian, (1952, 1958), Principles of Geochemistry, New York, John Wiley.

Mason, Brian, (1959), Nature, 183, 254.

Markov, A., (1924), Astronomische Nachrichten, 221, 65.

Mebane, A. D., (1956), Meteoritics, 1, No. 4, 405.

Merrill, G. P., (1911), Proc. U.S. Nat. Mus., 40, 482.

Michel, H., (1913), Annalen des (Vienna) (K. K.) Naturhistorische(n) (Hof-) museums, 27, 1.

Mueller, F. P., (1915), Geol. Mag., Decade VI, 2.

Nininger, H. H., (February, 1943), Sky and Telescope, 2, No. 4, p. 12 (March, 1943), 2, No. 5, p. 8.

Nininger, H. H., (1952), Out of the Sky, University of Denver Press, p. 58.

O'Keefe, J. A., (1959), Jour. Roy. Ast. Soc. of Canada, 53, 59.

Öpik, Ernst, J. (1937), Tartu Publication, 29, 46.

Öpik, Ernst J., (1958), Physics of Meteor Flight in the Atmosphere, Interscience Publishers, New York.

Oswald, Jan, (1942), Meteorické Sklo, Nákladem České Akademie věd a umění

Pettijohn, F. J., (1957), The Sedimentary Rocks, Harper and Bros., N. Y.

Pickering, W. H., (1922), Part I, Pop. Astr., 30, 632.

Pickering, W. H., (1923a), Part II, Pop. Astr., 31, 96.

Pickering, W. H., (1923b), Part III, Pop. Astr., 31, 443

Pickering, W. H., (1923c), Part IV, Pop. Astr., 31, 501.

Schoenberg, E., (1929), Handbuch der Astrophysik, 2, 1st half, p. 74.

Senior, T. B. A., and K. M. Siegel, (1958), Radar Reflection Characteristics of the Moon, Paris, URSI meeting.

Spencer, L. J., (1933), Mineralogical Magazine, 23, 387.

Spencer, L. J., (1937a), Mineralogical Magazine, 24, 503.

Spencer, L. J., (1937b), Nature, 139, 655.

Suess, F. E., (1898), Verhandlungen der K. K. Geol. Reichsanstalt, 387.

Suess, F. E., (1916), Centralblatt für Mineralogie, Geologie und Palaeontologie, Jahrgang 1916, p. 877.

Suess, H. E., (1951), Geochimica et Cosmochimica Acta, 2, 76.

Suess, H. E., Hayden, R. L., and M. G. Ingram, (1957), Nature, 168, 432.

Tilton, G. R., (1958), Geochimica et Cosmochimica Acta, 14, 323.

Urey, Harold C., (1955), Pub. Nat. Acad. Sci., 41, 27.

Urey, Harold C., (1958), Nature, 181, 1457.

Urey, Harold C., (1959), Nature, 183, 1114.

Varsavsky, C. M., (1958), Geochimica et Cosmochimica Acta, 14, 291.

Wirtz, C., (1915), Astronomische Nachrichten, 201, 289.

Wright, F. E., (1928), Proc. Nat. Acad. Sci., 13, 535.

Wylie, C. C., (1939), Pop. Astr., 47, 298.

FIGURE I

Section of an australite, showing flow structure. From Fenner, Transactions and Proceedings, Royal Society of S. Australia, 58, 75 (1934), after E. J. Dunn.

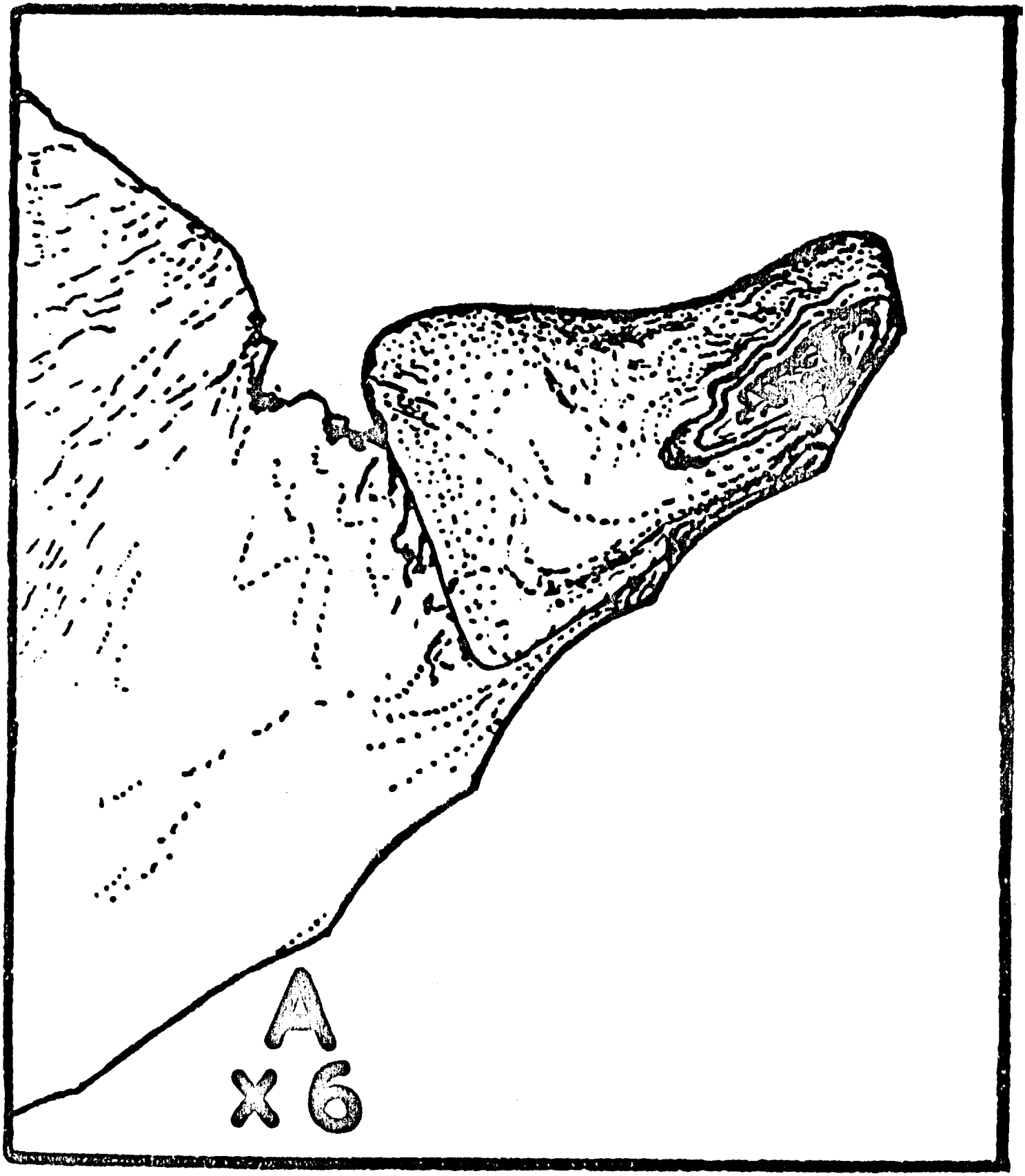
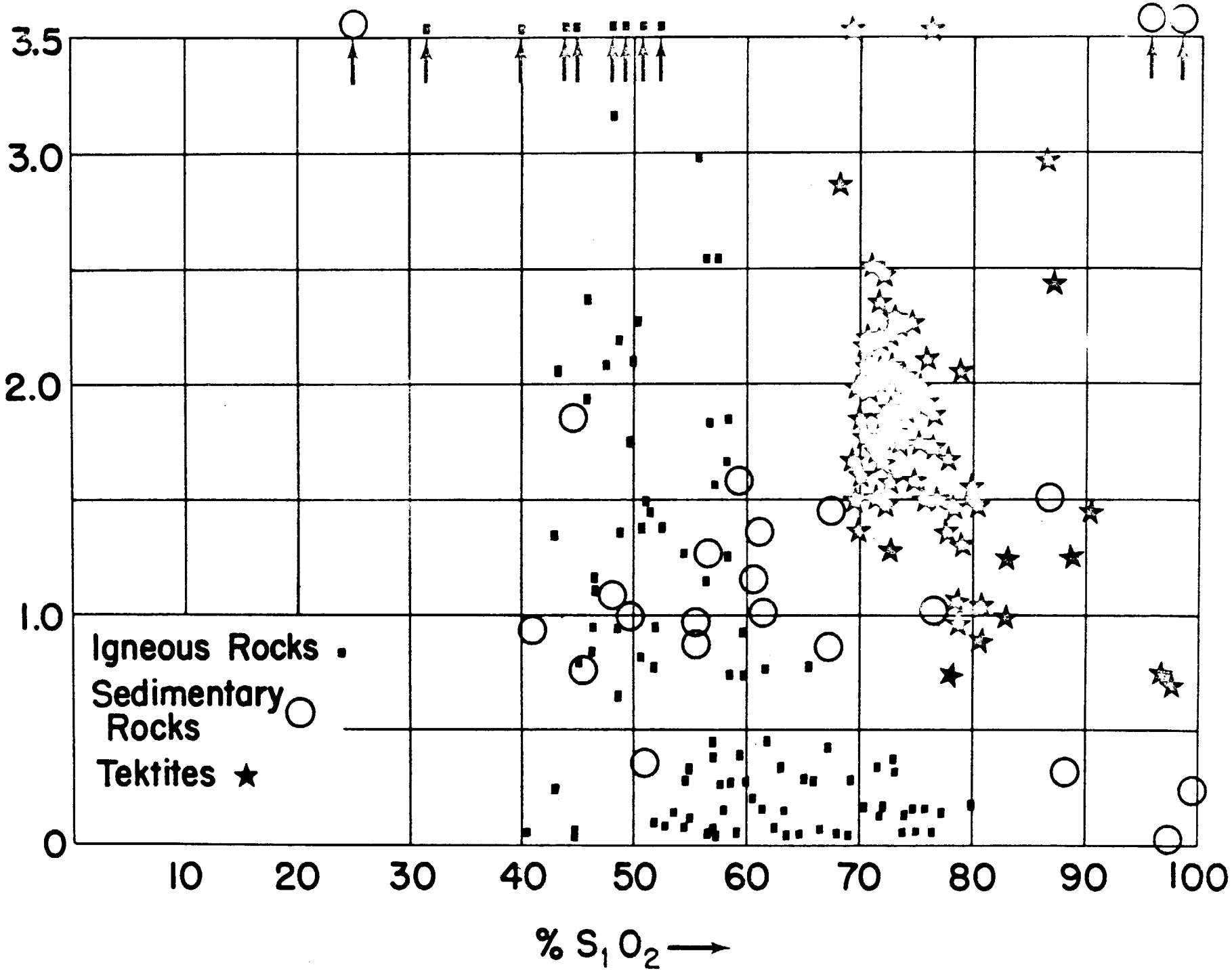

A
x 6

FIGURE 2

Plot of the ratio m, namely alkaline earths/alkalies, against silica.


3.5
3.0
2.0
1.0
0
10
20
30
40
50
60
70
80
90
100
Igneous Rocks
Sedimentary Rocks
Tektites
% S_1O_2 ⟶